

Received: 24 February 2025 • Revised: 05 April 2025 • Accepted: 09 May 2025

Research

doi: 10.22034/jcema.2025.543090.1164

Reducing Corrosion in Mechanically Stabilized Earth Systems Using Expanded Shale, Clay, and Slate Aggregates

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ABSTRACT

Corrosion of steel reinforcements in mechanically stabilized earth (MSE) walls poses a significant durability challenge, potentially shortening service life and raising maintenance costs. To assess whether engineered lightweight backfills mitigate this risk, eight expanded shale, clay, and slate (ESCS) aggregate specimens from five sources were experimentally compared with a conventional normal-weight aggregate. ESCS materials showed 20–40% lower unit weight and roughly 5–6 times higher water absorption than the normal-weight control. Their drained-condition electrical resistivity exceeded 10,000 $\Omega \cdot \text{cm}$, well above typical corrosivity thresholds ($\sim 3,000 \Omega \cdot \text{cm}$). Pore-water pH remained near-neutral (≈ 7.5 – 9.5) and chloride/sulfate contents were under $\sim 100/200$ ppm, aligning with established non-corrosive criteria. In accelerated wet/dry tests, steel embedded in coarse ESCS backfill exhibited corrosion rates of 2–10 $\mu\text{m}/\text{year}$, significantly lower than the 10–25 $\mu\text{m}/\text{year}$ observed in the normal-weight control. These findings suggest ESCS backfills create a more benign environment for reinforcement and indicate that current chloride/sulfate limits may be overly conservative for ESCS, supporting revisions to existing standards.

Keywords: Lightweight aggregates; Corrosion mitigation; Mechanically stabilized earth (MSE); Electrochemical characterization; Expanded shale, clay, and slate (ESCS)

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1. INTRODUCTION

Bridges are critical components of modern transportation networks, and there is a growing emphasis on sustainability and resilience in bridge infrastructure development. Bridge abutments, which support the bridge span and transition to approach embankments, play a pivotal role in overall system durability and safety. Mechanically stabilized earth (MSE) abutments have been widely adopted due to their economic efficiency

and reliable performance. However, the corrosion of steel reinforcements in conventional MSE backfills remains a significant concern, as it can substantially shorten the service life of these systems and escalate maintenance demands [1, 2]. Addressing reinforcement corrosion is therefore essential for extending bridge service life and reducing life-cycle costs in sustainable transportation infrastructure.

To address these challenges, attention has turned to rotary kiln-manufactured lightweight aggregates, including expanded shale, clay, and slate (ESCS) aggregates, as a sustainable alternative for MSE backfills. These engineered aggregates offer several advantageous properties from structural and geotechnical perspectives. Notably, ESCS backfill has a substantially lower unit weight than conventional sand or gravel, which leads to reduced earth pressures on abutment walls and lighter loads on foundations. The material's high porosity provides free drainage, preventing water buildup and thus reducing hydrostatic pressure behind the wall. Additionally, ESCS typically exhibits a high internal friction angle (often meeting or exceeding the 34°+ values required of quality MSE fill) that contributes to excellent stability and reinforcement pull-out resistance [3]. These properties help diminish structural demands, minimize settlement, and can streamline construction by requiring less compaction effort due to the aggregate's lower mass. Beyond these structural and geotechnical benefits, the use of ESCS aggregates has the potential to improve corrosion performance by creating a backfill environment that is inherently more benign to steel reinforcements.

Conventional design practice mitigates MSE reinforcement corrosion by enforcing strict backfill material criteria and standardized corrosion tests. Design specifications (e.g., AASHTO and FHWA guidelines) set limits on electrochemical properties such as electrical resistivity, pH, and salt content to classify a soil as non-corrosive [3]. For instance, typical requirements for MSE select fill include a minimum resistivity on the order of 3,000 $\Omega \cdot \text{cm}$, chloride content below ~100 ppm, and sulfate below ~200 ppm [3]. These parameters are measured with laboratory protocols like AASHTO T 288 (soil resistivity), AASHTO T 289 (pH), and related tests for chlorides and sulfates. Yet, such conventional corrosion assessment methods present limitations when applied to coarse backfill aggregates. Tests like AASHTO T 288 were developed for granular soils with a sufficient amount of fine material (passing a 2-mm sieve) and prolonged soaking of the sample. However, in practice, many aggregate backfills, including coarse normal-weight and lightweight aggregates, do not contain fines. Hence, the standard resistivity test does not apply to them, necessitating

adjustments or alternative methods to accurately measure their electrochemical properties [4].

Recent research initiatives have sought to quantify and capitalize on the electrochemical benefits of ESCS aggregates in MSE systems. Empirical evidence indicates that, despite sometimes exhibiting lower laboratory resistivity or higher soluble ion content, ESCS backfills do not exacerbate steel corrosion; in fact, measured corrosion rates of steel coupons in ESCS are often equal to or lower than those in conventional mineral aggregate backfills [1, 5]. This counterintuitive finding, lightweight aggregates registering aggressive values in standard tests yet yielding corrosion outcomes no worse (and sometimes better) than normal weight fills, highlights the need to re-examine traditional assessment methods. A recent national study has accordingly recommended updates to corrosion evaluation guidelines to account for the unique properties of lightweight aggregates [6]. One focus has been the adaptation of test methods to suit coarse ESCS materials better. Other studies reinforce the conclusion that coarse lightweight aggregates, though chemically active in lab conditions, show reduced corrosion activity in practical MSE environments [4, 7].

In addition to these engineering advantages, the sustainability and life-cycle performance of bridge abutments stand to benefit from ESCS lightweight backfills. The reduced density of ESCS translates to fewer required truckloads and lower material quantities for the same fill volume, potentially decreasing the energy, cost, and carbon footprint associated with construction. More importantly, improving the durability of MSE abutments by mitigating steel corrosion can extend the service life of bridges and reduce the frequency of inspections, repairs, or rehabilitation over decades of operation. This prolongation of maintenance cycles yields significant life-cycle cost savings and minimizes disruptions to service, aligning with broader sustainable infrastructure goals. By demonstrating that ESCS aggregates can meet the necessary structural and durability requirements while alleviating corrosion concerns, the present study highlights their potential to contribute to more resilient, cost-effective, and environmentally friendly transportation infrastructure [6, 8].

2. METHODOLOGY

2.1. Experimental Procedure:

This study evaluated eight samples of expanded shale, clay, and slate (ESCS) lightweight aggregates from five sources and one single-sourced normal-weight aggregate as the control. The goal was to characterize their physical and electrochemical properties and to understand how using ESCS aggregates might influence corrosion of steel reinforcement in mechanically stabilized earth (MSE) structures [9, 10]. Each aggregate sample was obtained in as-received condition and kept sealed to prevent any alteration before testing. By examining a range of lightweight aggregate sources alongside a conventional aggregate, the experimental design provides comparative insight into the performance of sustainable lightweight backfills in infrastructure applications [1]. Notably, previous research has highlighted the need to extend bridge abutment service life and reduce maintenance by mitigating reinforcement corrosion in MSE systems [1, 7]. Using lightweight aggregates in these systems can contribute to this goal by reducing loads and improving durability, ultimately lowering life-cycle costs and environmental impacts [9]. In line with these objectives, our methodology builds on established standards and past studies of corrosion in MSE walls [5], adapting them to evaluate the innovative use of ESCS materials in backfills.

Standard laboratory protocols (ASTM, AASHTO, and TxDOT) were followed to measure key physical characteristics, chemical properties, and indicators of corrosivity for each aggregate. Gradations, densities,

and water absorptions were determined using ASTM C136, ASTM C127 (coarse aggregate), and ASTM C128 (fine aggregate), respectively [9, 10]. Electrochemical tests were then conducted to assess parameters known to affect steel corrosion in soil backfills. These included electrical resistivity (following AASHTO T 288 for soil resistivity and the Texas DOT procedure Tex-129-M for coarse aggregates), pore water pH (AASHTO T 289 and ASTM D4972/Tex-620 methods), and soluble sulfate and chloride ion content of the aggregate samples [9, 11]. Figure 1 shows several of the aggregate samples stored in sealed buckets before testing, underscoring the care taken to preserve their moisture state and chemistry. All chemical and electrochemical tests were performed on solutions or specimens prepared according to the respective standard (for example, specified soil-to-water ratios and conditioning times for pH and ion tests) to ensure consistency with industry practices [12]. Wherever applicable, multiple test methods were applied to the same property for a more robust evaluation – for instance, using both the AASHTO two-electrode soil box and the Tex-129-M large-box procedure for resistivity – so that results would reflect field conditions as closely as possible [13, 14]. This comprehensive testing matrix (covering particle size distribution, specific gravity, absorption, resistivity, pH, and ion content) provides a holistic view of each aggregate's properties under controlled conditions.



Figure 1. Sample aggregates stored in sealed containers to preserve the as-received condition before testing.

In adapting the standard test protocols, certain modifications were introduced to simulate real-world service environments for MSE backfill better. One important consideration was particle size: conventional corrosivity tests often require passing the sample through a 2 mm (No. 10) sieve, focusing only on the fine portion [15]. However, MSE backfill in the field contains a full range of particle sizes, and excluding the coarse fraction can skew measurements (for example, laboratory resistivity values can be deceptively low when only fines are tested) [13, 14]. To address this, we performed parallel resistivity and pH tests on both the standard fine fraction and on samples that included the coarse aggregates using larger soil boxes as per Tex-129-M [13]. This approach follows recommendations from recent studies that found allowing larger particles in the test yields results more representative of field conditions [14]. Similarly, the pH testing procedure was adjusted by using a modified Tex-620 method (Tex-620-M) that accommodates highly absorptive lightweight aggregates and ensures sufficient solution volume for accurate readings [12]. All samples were also tested in various moisture states – for instance, some resistivity measurements were taken after an initial soaking period versus others on air-dried material – to capture the effects of moisture variation that actual backfills experience in service [4, 7]. These adjustments, while staying within the framework of official test standards, were crucial for capturing the actual behavior of the aggregates under in situ conditions.

Overall, the experimental procedure was designed to ensure that laboratory measurements correspond closely to performance in the field, thereby yielding

2.2. Measurements

The basic physical characteristics of the ESCS aggregates were first determined to assess their suitability as free-draining, durable backfill. Grain size distribution was evaluated by sieve analysis (ASTM C136), ensuring that each sample met gradation requirements with minimal fines. Specific gravity and water absorption were measured for coarse and fine fractions following ASTM C127 and C128, respectively. The ESCS aggregates showed 20–40% lower bulk density and 5–6 times higher water absorption than normal-weight gravel. This pronounced porosity, a product of the rotary-kiln expansion process, is beneficial for internal curing and drainage but also means the aggregates can retain

results relevant for design and long-term durability assessments. Each aggregate's gradation was classified into “coarse” and “fine” components (particles retained on or passing the 2 mm sieve, respectively) to examine the influence of particle size distribution on corrosion-related properties [10]. Physical properties like bulk density and absorption were measured right after sample preparation to incorporate the aggregates' natural moisture content and pore structure, which are known to affect electrochemical behavior [10]. The use of sealed containers (Figure 1) until the moment of testing ensured that the aggregates' internal moisture and any reactive salts were preserved as in real stockpile conditions. Testing under “as-received” conditions (and after controlled conditioning like soaking or drying as needed per test) means the data reflect realistic scenarios that MSE reinforcement might encounter [4, 7]. In addition, some of the critical tests were repeated by an independent certified lab for verification, adding confidence that the results are reliable for engineering applications [9]. By combining standardized methods with targeted modifications informed by current research, this methodology provides a reliable basis for comparing lightweight and normal-weight aggregates in terms of corrosion potential and suitability for sustainable infrastructure projects. The careful alignment with ASTM/AASHTO guidelines and the inclusion of state DOT innovations ensure that the findings can be readily translated into practice, helping identify backfill materials that minimize corrosion risk while offering the benefits of lightweight aggregates [5, 11].

moisture in their pores. These physical properties confirm that ESCS materials meet the gradation, drainage, and weight characteristics required for use in MSE applications, potentially reducing loads on structures while maintaining proper performance [2, 5, 7].

The electrical resistivity of each aggregate was measured using AASHTO T 288, ASTM G187, and Tex-129-M protocols. Testing was conducted under both saturated and drained conditions to replicate the range of moisture states typically experienced by backfill in field applications. The ESCS aggregates consistently exhibited significantly higher resistivity values under drained conditions, often by an order of

magnitude, compared to their saturated counterparts. This behavior is consistent with the well-established influence of moisture and ion concentration on electrical conductivity. Coarser gradations, due to lower moisture retention, showed particularly elevated resistivity levels. In all cases, the drained-state resistivity exceeded $10,000 \Omega \cdot \text{cm}$, a threshold well above what is considered aggressive for corrosion risk, confirming that ESCS aggregates are generally non-conductive to corrosion-prone environments [1, 6, 8].

To further understand their chemical impact on steel corrosion, the aggregates were evaluated for pH, sulfate, and chloride concentrations. pH testing followed AASHTO T 289 and ASTM D4972, while sulfate and chloride levels were assessed using Tex-620-M and procedures comparable to ASTM G187. Across the samples, pH values were consistently near-neutral to mildly alkaline, ranging between 7.5 and 9.5. These conditions are within accepted ranges for use with metallic reinforcements and do not pose a threat of acid-induced corrosion. Additionally, chloride concentrations remained below the commonly cited 100 ppm threshold, and sulfate levels were under 200 ppm, both falling within safe limits used to classify non-aggressive soils. Despite minor variations among sources, none of the ESCS aggregates tested exceeded these critical values, indicating a low risk of chemically driven corrosion initiation [1, 6, 7].

To validate these electrochemical indicators with direct performance data, both galvanized and carbon steel coupons were embedded in aggregate samples and exposed to cyclic wetting and drying over periods of 7, 14, and 28 days. Corrosion rates were determined through gravimetric weight loss and coating thickness measurements. As shown in Figure 2, ESCS aggregates either matched or exceeded the performance of the normal-weight control, with galvanized coupons consistently exhibiting corrosion rates well below critical thresholds. As expected, carbon steel coupons degraded at approximately three times the rate of galvanized ones. However, no ESCS sample resulted in significantly higher corrosion, and several performed better, likely due to improved drainage and reduced moisture retention. These results support the overall conclusion that ESCS aggregates offer a stable, non-aggressive environment for embedded steel, confirming their suitability for long-term use in MSE walls with metallic reinforcements [1, 3, 7].

In this study, corrosion rate is reported as thickness loss ($\mu\text{m}/\text{year}$) derived from gravimetric weight-loss measurements of steel coupons. While corrosion current density is sometimes expressed in $\mu\text{A}/\text{cm}^2$, the values presented here correspond to actual material loss rates.

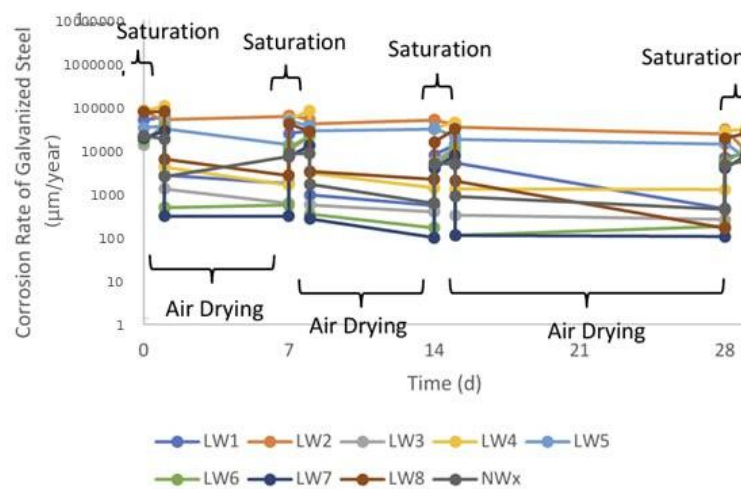


Figure 2. Corrosion Rate of Galvanized Steel Subjected to Various Moisture Conditions Throughout Time.

3. RESULTS AND DISCUSSION

Electrochemical and physical evaluations were conducted on a range of aggregate samples, including expanded shale, clay, and slate (ESCS) lightweight aggregates and a conventional normal-weight

aggregate, all prepared under controlled laboratory conditions. The testing program encompassed key parameters such as grain size distribution, specific gravity, water absorption, pH, electrical resistivity,

and soluble ion concentrations to provide a broad characterization of each material's performance. Corrosion resistance was further assessed using embedded galvanized and carbon steel coupons subjected to simulated wetting-drying cycles. This

3.1. Physical Properties

The physical characterization indicates that ESCS aggregates are suitable for MSE applications. Compared with the normal-weight control, ESCS showed a 20 to 40 percent lower bulk density, which reduces earth pressures on walls and demands on foundations [15]. Their water absorption was approximately 5 to 6 times higher than that of the conventional aggregate, reflecting greater porosity

comprehensive dataset serves as the basis for analyzing and comparing the durability potential of ESCS aggregates in mechanically stabilized earth systems.

that affects moisture transport and drainage behavior [16]. [Figure 3](#) plots bulk density against water absorption for all tested materials and shows ESCS samples clustering at lower densities and higher absorption than the normal-weight aggregate, clearly distinguishing the two material groups.

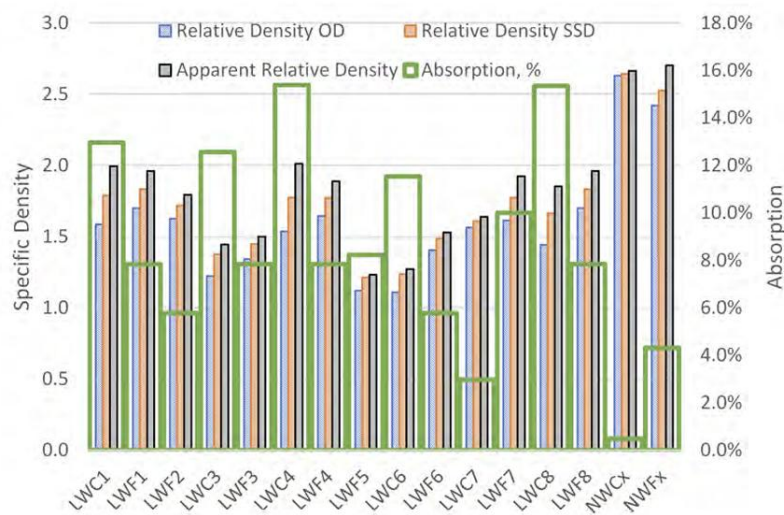


Figure 3. Specific Density of Aggregate Samples.

3.2. Electrical Resistivity

The resistivity tests revealed significant differences between coarse and fine ESCS aggregates. Coarse aggregates consistently exhibited higher resistivity values, indicating greater corrosion resistance. Additionally, resistivity was higher in drained conditions, emphasizing the importance of proper drainage to minimize corrosion risk [7]. [Table 1](#) presents the values obtained from the standard methods and, for each category, the ranges report the minimum to maximum resistivity observed across all specimens under the stated moisture condition. [Figure 4](#) further illustrates these trends and groups results by method: AASHTO T 288 represents fines-based soil-box measurements, Tex-129-M is the large-box method that accepts coarse particles, ASTM G187 is a two-electrode procedure, and the 24-hour saturated series reflects fully soaked

specimens. Tex-129-M in drained condition consistently plots at the top, showing that inclusion of coarse particles and effective drainage yield much higher resistivity consistent with a less corrosive environment. By contrast, T 288 and 24-hour saturated values cluster lower, indicating moisture-driven increases in conductivity for fines-dominated or wet specimens. The third-party T 288 results closely match the in-house T 288 bars, indicating acceptable reproducibility, and the normal-weight control tends toward the lower end under comparable conditions, while coarse ESCS in drained Tex-129-M consistently occupies the upper tier.

Table 1. Summary of Resistivity Test Results ($\Omega \cdot \text{cm}$)

Material Type	Condition	Resistivity ($\Omega \cdot \text{cm}$)
Coarse ESCS Aggregates	Drained	10,000 - 15,000
Coarse ESCS Aggregates	Saturated	5,000 - 8,000
Fine ESCS Aggregates	Drained	4,000 - 6,000
Fine ESCS Aggregates	Saturated	1,500 - 3,000

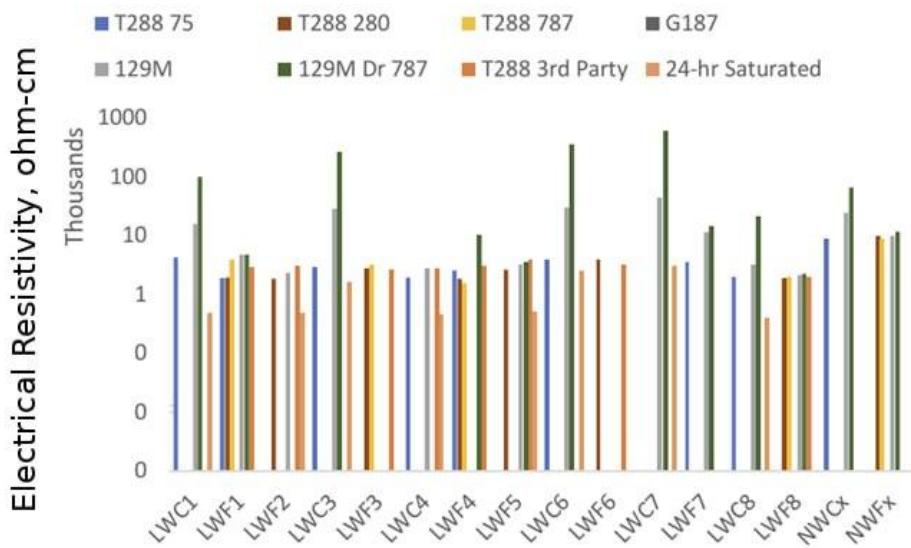


Figure 4. Electrical Resistivity Results Using Standard Methods

3.3. pH Levels of Water

The pH levels of ESCS aggregates ranged from 7 to 10, consistent with the optimal range for minimizing corrosion in steel reinforcements. Variations between testing methods revealed minor discrepancies,

further supporting the need for standardized testing protocols [17]. The results are visualized in Figure 5, showing the pH values of selected samples under AASHTO T 289 standards.

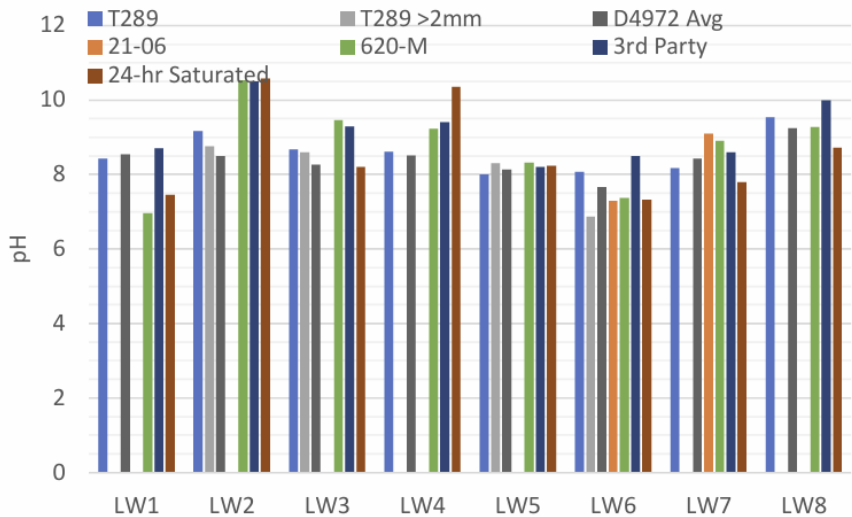


Figure 5. pH of Selected Samples Using AASHTO T 289

3.4. Sulfates and Chlorides

Sulfate and chloride contents in ESCS aggregates were within acceptable thresholds, confirming low corrosivity. For sulfates, values varied by source and method, with the maximum observed for LW2 under the third-party procedure at about 2,800 mg/kg, and the minimum for the NWCx control at below 100 mg/kg. Across methods, third-party results tended to be the highest, T290 and 620-M formed an intermediate band, and 24-hour saturated values were

generally the lowest, indicating a clear method effect on measured sulfate content [18]. For chlorides, measured concentrations remained low across the tested aggregates, supporting compatibility with steel reinforcement [19]. Figure 6 compares sulfate contents for each sample across the standardized methods and highlights these maxima, minima, and method-dependent trends.

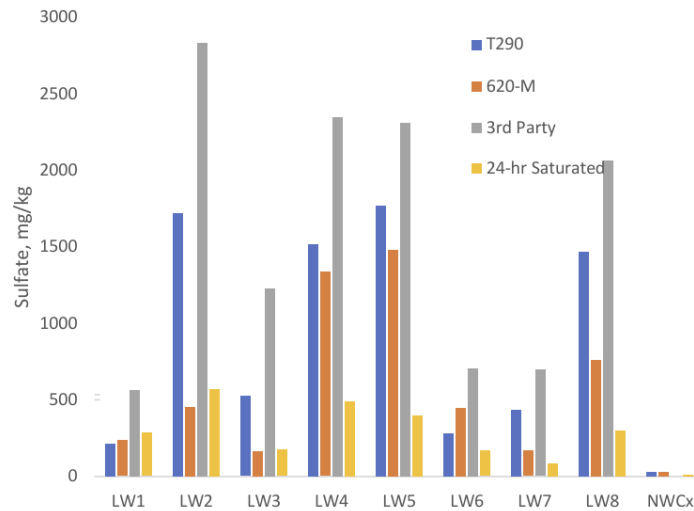


Figure 6. Comparison of Sulfate Contents of Selected Samples Using Different Standards.

The corrosion rates of steel coupons embedded in ESCS aggregates were consistently lower than those observed in normal-weight aggregates. Wetting-drying cycles showed that ESCS aggregates'

enhanced drainage properties significantly reduced moisture retention, thereby lowering corrosion risks [20]. The relationship between corrosion rates and wetting-drying cycles is detailed in Figure 7.

3.5. Limitations

The evidence presented here is based on a controlled, comparative program designed to evaluate ESCS backfills against a normal-weight control using standardized electrochemical and physical tests adapted for coarse materials. While the data consistently indicate reduced corrosivity for ESCS, the study does not encompass every field scenario, exposure history, or product variant. The following points summarize the principal constraints that should guide interpretation of the results.

- 1- Sampling scope. Eight ESCS aggregates from five sources and one normal-weight control were tested, supporting comparative trends but not exhaustive generalization to all ESCS products or site conditions.
- 2- Laboratory conditions vs field behavior. Measurements were conducted under controlled preparation, compaction, and moisture states. Actual backfills experience construction variability, spatial

heterogeneity, and transient moisture regimes that may alter absolute values even if relative trends persist.

- 3- Exposure duration. Corrosion was assessed under accelerated wet-dry cycling at 7, 14, and 28 days, which does not represent multi-year or seasonal field histories.
- 4- Method adaptations for coarse aggregates. Procedures such as Tex-129-M large-box resistivity and modified handling for highly absorptive materials improve relevance for ESCS but limit direct, like-for-like comparison with criteria developed for fines-based soil tests.

These limitations do not change the direction of the findings, but they indicate where caution is warranted when extrapolating to long-term, in-situ performance. Future work should include longer monitoring periods, instrumented field sections across climates, and expanded sourcing to capture

variability, alongside studies that systematically vary moisture and de-icing exposures..

3.6. DISCUSSION

The findings from this study underscore the significant advantages of expanded shale, clay, and slate (ESCS) aggregates for mechanically stabilized earth (MSE) applications, demonstrating their capacity to address critical engineering and environmental challenges. A key benefit of ESCS aggregates is their reduced density, approximately 20-40% lower than that of traditional normal-weight aggregates. This lower density diminishes dead loads on MSE systems, enabling more efficient structural designs and shorter foundations. These properties result in cost savings,

increased construction efficiency, and enhanced long-term stability. Additionally, the granular nature of ESCS aggregates promotes efficient drainage, reducing the risk of hydrostatic pressure and water-induced structural damage. Adequate drainage is particularly crucial in high-moisture environments, where water retention may compromise structural integrity [21]. Figure 7 highlights the combined impact of reduced structural demands and improved drainage, illustrating how these aggregates support resilient and cost-effective infrastructure systems.

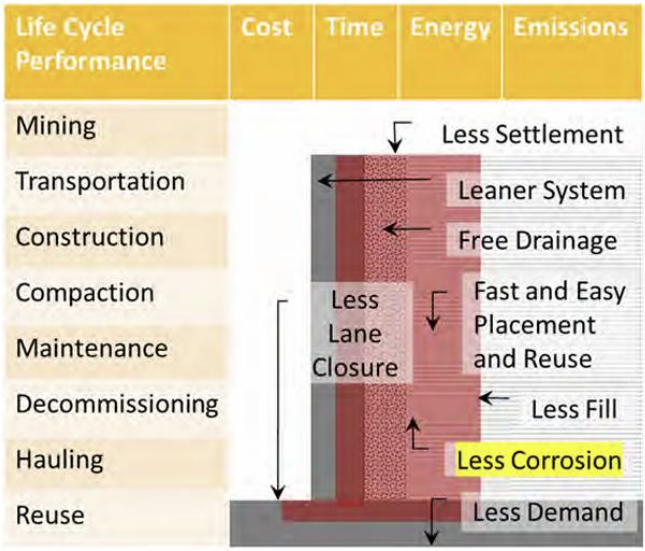


Figure 7. Schematic Illustration of Lightweight Aggregate Benefits in MSE Applications.

The electrochemical characteristics of ESCS aggregates further enhance their suitability for MSE applications. The study found that coarse aggregates demonstrated significantly higher resistivity values than their finer counterparts, especially under drained conditions. Higher resistivity correlates with lower corrosion risks for embedded steel reinforcements [8]. Table 2 details the corrosion rates in ESCS backfills, expressed in $\mu\text{m}/\text{year}$, revealing consistently lower values compared to those in normal-weight aggregates. These results highlight the superior performance of ESCS materials in mitigating corrosion. Table 2 shows that steel in normal-weight aggregate corrodes at 10 to 25 $\mu\text{m}/\text{year}$, whereas coarse ESCS limits corrosion to 2 to 10 $\mu\text{m}/\text{year}$ and fine ESCS to 4 to 12 $\mu\text{m}/\text{year}$. In

relative terms, the worst-case rate in coarse ESCS (10 $\mu\text{m}/\text{year}$) is about 60 percent lower than the worst-case in normal aggregate (25 $\mu\text{m}/\text{year}$), and typical values indicate a 50 to 70 percent reduction. The advantage of coarse ESCS is consistent with its higher drained resistivity and improved drainage, which reduce moisture retention and ionic conductivity; fine ESCS is slightly less favorable than coarse ESCS, likely due to greater moisture hold and contact area, yet it still outperforms normal aggregate. For design context, a rate of 10 $\mu\text{m}/\text{year}$ corresponds to roughly 0.75 mm thickness loss over 75 years, compared with about 1.9 mm at 25 $\mu\text{m}/\text{year}$, illustrating the potential life-cycle benefit when ESCS is used.

Table 2. Range of Corrosion Rates for Aggregate Groups

Aggregate Type	Corrosion Rate (µm/year)
Normal-Weight Aggregates	10-25
Coarse ESCS Aggregates	2-10
Fine ESCS Aggregates	4-12

The pH levels of ESCS aggregates, ranging between 7 and 10, further support their corrosion-resistant properties. This range aligns with thresholds that minimize steel degradation, as both highly acidic and highly alkaline environments accelerate corrosion. Additionally, the low sulfate and chloride levels in ESCS aggregates confirm their chemical stability, making them ideal for long-term infrastructure projects.

To fully leverage these benefits, revisions to current standards are recommended. Existing ASTM and AASHTO guidelines on permissible sulfate and chloride levels could be updated to reflect the improved performance of ESCS aggregates. For instance, increasing allowable limits for these

chemical properties would facilitate broader adoption of ESCS materials while maintaining safety and durability standards [22]. Additionally, testing protocols should be revised to account for the distinct properties of coarse aggregates, as current methods often prioritize finer materials and fail to capture the full performance spectrum of ESCS aggregates. Future research should investigate the behavior of ESCS aggregates under varied climatic and loading conditions. Incorporating these findings into lifecycle cost analyses would provide a comprehensive understanding of their economic and environmental benefits, supporting their integration into mainstream construction practices.

4. CONCLUSION

This work experimentally compared ESCS lightweight aggregates with a normal-weight control to evaluate their suitability as MSE backfills under standardized electrochemical and physical testing, including adapted procedures for coarse materials. The results consistently indicate that ESCS backfills create a less corrosive environment for metallic reinforcement while offering structural and constructability advantages. Key findings from this study include:

- 1- Physical properties. ESCS aggregates showed 20–40 percent lower bulk density and approximately 5–6 times higher water absorption than the normal-weight aggregate, separating clearly from the control in the density–absorption plot. These properties reduce earth pressures and influence moisture transport.
- 2- Electrical resistivity. Coarse ESCS under drained conditions exceeded 10,000 Ω·cm, with drained values consistently higher than saturated values and large-box methods reflecting the effect of including coarse

- particles. These trends indicate lower corrosion risk when drainage is effective.
- 3- pH and soluble ions. Pore-water pH remained near-neutral to mildly alkaline (about 7 to 10), while chloride and sulfate contents were low and within accepted, non-aggressive limits across methods, with method-dependent variation captured in the sulfate comparisons.
- 4- Corrosion performance. Coupon tests showed corrosion rates of about 2 to 10 µm/year in coarse ESCS, 4 to 12 µm/year in fine ESCS, and 10 to 25 µm/year in normal-weight aggregate, aligning with the resistivity and moisture findings and indicating substantial reductions in expected thickness loss over service life.

Implications and next steps. The combined physical and electrochemical evidence supports broader use of ESCS backfills to enhance durability and reduce lifecycle costs in MSE structures. Practice guidance would benefit from recognizing coarse-aggregate test methods and re-examining chloride, sulfate, and

resistivity limits where appropriate for ESCS materials. Future phases should include longer-duration and field-instrumented studies, expanded sourcing to capture variability, and targeted

evaluations under temperature changes, de-icing exposures, and representative loading to further validate long-term performance.

FUNDING/SUPPORT

The California State University Transportation Council and Fresno State Transportation Institute funded this project.

ACKNOWLEDGMENT

The authors acknowledge materials donated by Arcosa Lightweight, Buildex, Carolina Stalite, Holcim Utelite, and Norlite and testing equipment lent by the Expanded Shale, Clay and Slate Institute (ESCSI). The authors also appreciate the assistance of Arthur Hauzer, BSc, the Lyles College of Engineering laboratory engineer at California State University, Fresno.

AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interest with respect to the authorship and/or publication of this paper.

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